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TRANSIENT DEVELOPMENT OF STRATIFICATION IN A PARTIALLY DIVIDED ENCLOSURE

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ABSTRACT

In passive solar heating of buildings or in compartment fires, we are concerned with the development of thermal stratification when two rooms at different temperatures are connected by the opening of a door. We have performed experiments and numerical calculations aimed at this application. The experiments consist of flow visualization and temperature measurements obtained when isolated halves of a tank containing water at two different temperatures are suddenly connected to allow flow between the zones. Two significant findings from this work are: 1) the presence of internal waves excited by the onset of flow through the doorway which have not normally been observed in past laboratory experiments, and 2) the equilibration time is found to be in general agreement with that predicted by a formula from a simple orifice model that we describe. Work is progressing on numerical simulations using two core stratification models connected by an orifice including entrainment in the neighborhood of the connection.

NOMENCLATURE

- A planform area of a room, m^2
- b doorway width, m
- g acceleration of gravity, m/s^2
- h half of doorway height, m
- h_1 location of thermocline measured from mid-height of doorway, m
- H dimensionless thermocline position, h_1/h
- Q volumetric flow rate, m^3/s
- t time, s
- t^* dimensionless time, t/τ
- V horizontal component of velocity, m/s
- y vertical coordinate measured from mid-height of doorway, m
- ρ density, kg/m^3
- τ time constant defined by Eq. (6)

Subscripts

- avg average
- c cold room
- h hot room

INTRODUCTION

Buildings are complex partially divided enclosures where the flow of fluid and heat (heating and air-conditioning) is a major concern. In passive-solar heated or cooled structures, and in compartment fires, one is concerned with all aspects of flow and energy transport arising from natural convection, and there has been considerable work reported in recent years. The passive solar program of the U.S. Department of Energy has funded a variety of investigations including full-scale testing of actual houses (Balcomb and Yamaguchi, 1983; Balcomb et al. 1984; Balcomb and Jones, 1985), construction and operation of full-scale simulated housing (Hill et al. 1985; Kahwaji et al. 1985), model experiments using water (Nansteel and Greif, 1981; Kirkpatrick and Bohn, 1983; Nansteel and Greif, 1984; Kirkpatrick and Bohn, 1985; Anderson et al. 1985) and Freon (Yamaguchi, 1984), and numerical simulations (Bauman et al. 1980; Gadgil et al. 1984; Jones et al. 1985a). For the most part, these programs emphasize steady flows, and in fact one of the major problems in experimental work is to construct a facility with small enough thermal inertia so that the transient passes quickly. Even so, 24 hours is not an unusual requirement for the attainment of steady state.

But in reality, most practical systems are continually undergoing change, and it would seem appropriate to give more consideration to important features of the transient. Of course, many have carried out transient studies: analytical (Sakurai and Matsuda, 1972; Jischke and Doty, 1975), numerical experiments (Gallagher et al. 1978; Patterson and Imberger, 1980;

Lee and Korpela, 1983; Han, 1984; Hyun, 1985), and laboratory experiments (Yewell et al. 1982; Hamblin and Ivey, 1983; Ivey, 1984). But these are all for undivided enclosures (i.e. a single room) where the wall boundary layers are the driving mechanism.

The work described here is concerned with the transient flow through a doorway connecting two rooms of an enclosure, the rooms being initially at different temperatures. The experiment is carried out in a small water tank, and the transient occurs in about 100 seconds. The flow is driven by the hydrostatic pressure gradient resulting from the difference in water density between the rooms, and one of the major objectives in running the experiment was to determine whether the doorway velocity distribution of Brown and Solvason (1962) would adequately describe the transient doorway flow. Furthermore, it is a simple experiment and may provide an effective test for the validation of computer programs.

DESCRIPTION OF THE EXPERIMENT

A rectangular, glass aquarium (nominally 50 cm long, 23.5 cm wide and 29 cm high) is divided into two equal rooms by a plexiglass dividing-wall (see Figure 1). A 4.0-cm-wide x 20.1-cm-high doorway is centered

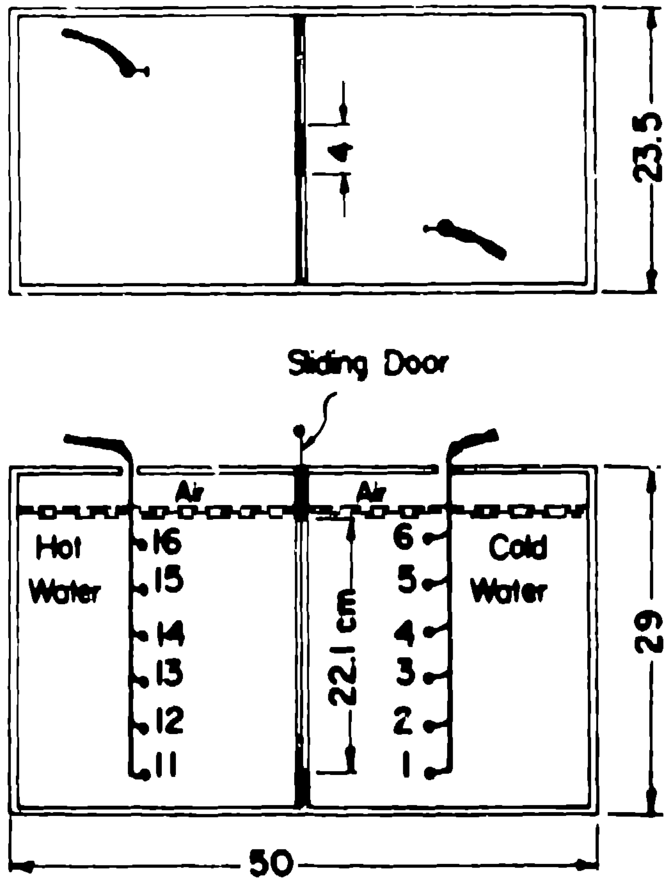

Fig. 1 Schematic of enclosure showing thermocouple locations and door of height 2 h = 22.1 cm and of width b = 4 cm (drawn approximately to scale).

in the dividing wall with threshold 3 cm above the tank floor. Each room has a vertical rake of 6 copper-constantan thermocouples located as shown in Figure 1. Each thermocouple was calibrated to within ±0.1°C. The doorway opening is covered with a 3-mm-thick plexiglass plate which slides vertically through a slit in the cover plate. No insulation is required for the system, since the time constant for heat loss to the surroundings is over an hour, whereas the entire experiment runs in about 4 minutes. The outside surfaces of the tank are, in effect, insulated.

The tank is filled with water to 1.0 cm above the top of the doorway, leaving a 3.0-cm air gap below the cover plate. About 1.5 liters of water is removed from the left side, heated to about 95°C, and then poured back with vigorous stirring to produce a uniform temperature. The fluid motion is damped with a grass broom, the top is set in place, thermocouple rakes installed, data logger started, and then the door is gently removed. The elapsed time from pouring the hot water to opening the door is about 2 minutes.

RESULTS FROM THE EXPERIMENT

Temperatures are logged at 5 second intervals, and the results for a single test are plotted in Figure 2.

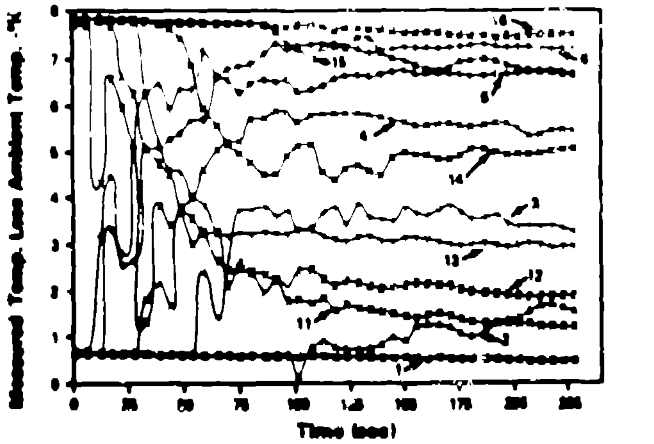

Fig. 2 Time-temperature history for a single experiment. Thermocouple numbers are given with each curve (see Fig. 1 for their locations).

Note that thermocouples 1 to 6 in the cold tank were initially at 24.6°C to 24.8°C and numbers 11 to 16 in the hot tank were initially at 31.6°C to 31.8°C. The ambient temperature was 23.9°C. At time of zero the door is opened, and a counterflow develops immediately (observed visually by means of multicolored dyes as described below) with flow from hot to cold in the upper half of the doorway, and from cold to hot in the lower half. The hot water flow rises to the top of the cold side, and at 7 seconds the upper thermocouple on the cold side (number 6) responds with a sudden rise in temperature. At 7 seconds the lowest thermocouple on the hot side (number 11) responds with a sudden drop in temperature. These thermocouples experience wide gyrations in temperature resulting from internal waves excited by the rapid onset of flow. The waves are observed visually as discussed below. Such waves are evident in all of the curves, and have a frequency ranging from 0.05 to 0.1 hertz. This compares with a buoyancy frequency of 0.045 hz based on the initial temperature difference and the doorway height. The thermocouples respond in succession as they are engulfed by the inflowing fluid, and after 200 seconds the tank approaches a state of stratification that is the same in both rooms. The development of the stratification temperature distribution is also shown in Figure 3 where we note that the cold room thermocouple rake is about 3 mm lower than in the hot room.

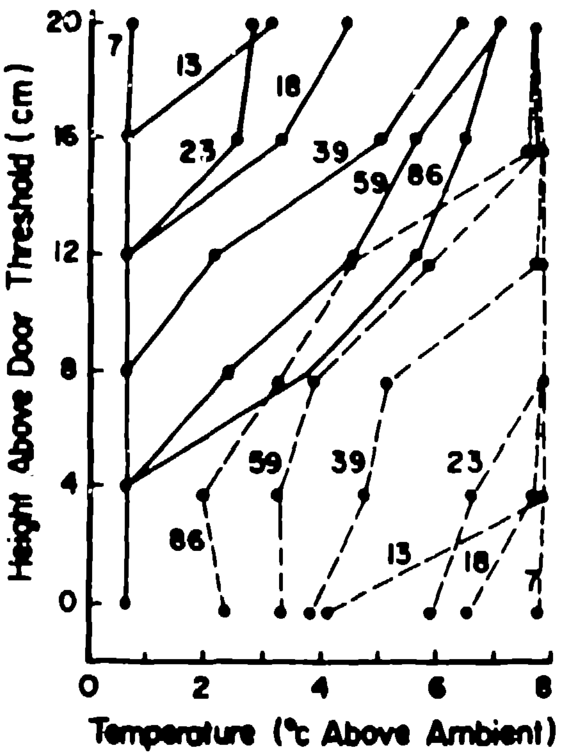

Fig. 3 Development of the stratification temperature distribution. Hot room shown in solid lines and cold room shown by dashed lines. Thermocouple data is indicated by a dot. Time (in seconds) is indicated to the left of each curve. Bottom of door is datum. Top of door is 22.1 cm, and top of tank is 25.72 cm.

The central thermocouple pairs (3 and 13, and 4 and 14) overshoot their equilibrium values crossing each other at 72 and 89 seconds respectively. This indicates that the inertia of the doorway flow coupled with the capacitance of the liquid storage in each room results in a very low frequency and highly damped "sloshing mode" with a period of over 100 seconds. This overshoot is also evident in Figure 3 by comparing the two curves corresponding to the time of 86 seconds.

A SIMPLE MODEL

Although the problem may be solved using numerical methods, a simpler approach to estimate development of the flow is to regard the hot and cold fluids as nonmixing, and adopt the model of Brown and Solvason (1962) for the velocity distribution in the doorway. The model assumes that the velocity is induced by a horizontal pressure difference across the doorway resulting from the difference in vertically integrated fluid density profiles in the two rooms. The horizontal pressure difference is zero at the mid-height of the doorway, and varies linearly with distance measured vertically from the doorway center.

Application of an inviscid orifice equation produces a vertical distribution of horizontal velocity that varies as the square root of distance from the doorway center. With the hot room placed on the left, the flow in the doorway upper-half is to the right, and to the left in the lower-half as illustrated in Figure 4. We need consider only the upper-half, for which the velocity distribution is

$$V = \sqrt{2\, g\, y\, (\rho_c - \rho_h)/\rho_{avg}} \qquad (1)$$

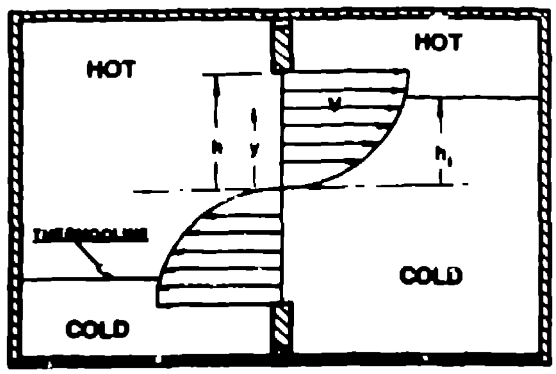

Fig. 4 Schematic elevation view for the model of exchange through a doorway assuming no mixing.

Although this is strictly a hydrostatic model, which takes no account of the actual flow, it has proved to be quite satisfactory for quasi-steady, high-Rayleigh-number flows (Balcomb et al. 1984). However, its accuracy in transient flows has not been substantiated. An analogous situation is the application of Torreccelli's equation for steady flow through an orifice to the transient emptying of a tank, which is well known to yield accurate results.

If the cold and hot fluids were nonmixible, the hot flow from the left would remain at constant temperature and would rise to the top of the right-hand room forming a hot layer which grows downward from the water surface (a similar cold layer would form on the floor of the hot room and develop upward). As the thermocline descends in the cold room (and rises in the hot room), the pressure difference is modified, and so is the velocity distribution. Looking only at the cold room, where the thermocline is located at h_1 (see Figure 4), the velocity distribution in the doorway upper-half is:

$$\begin{aligned} V &= \sqrt{2\, g\, y\, (\rho_c - \rho_h)/\rho_{avg}}, && \text{for } 0 \le y \le h_1 \\ V &= \sqrt{2\, g\, h_1 (\rho_c - \rho_h)/\rho_{avg}}, && \text{for } h_1 \le y \le h \end{aligned} \qquad (2)$$

The total volume flow rate from the hot to the cold room is obtained by integration from y = 0 to h with the result that

$$Q = b\,[h - h_1/3]\,\sqrt{2\, g\, h_1\, (\rho_c - \rho_h)/\rho_{avg}} \qquad (3)$$

where b is the doorway width. The thermocline moves vertically with a velocity given by

$$dh_1/dt = -Q/A \qquad (4)$$

where A is the planform area of each room. By use of Eq. (3), this can be expressed in normalized form as

$$dH/dt^* = (H/3 - 1)\sqrt{H} \qquad (5)$$

where the variables are defined as follows:

$$t^* \equiv t/\tau, \quad H \equiv h_1/h$$
$$\tau \equiv (A/b)\,\left(2\,g\,h\,(\rho_c - \rho_h)/\rho_{avg}\right)^{-1/2} \qquad (6)$$

For the conditions of our experiment, we have

$$A = 574.4\ \text{cm}^2, \quad b = 4\ \text{cm}, \quad h = 11.04\ \text{cm}$$

$$\rho_c = 997.13\ \text{kg/cm}^3, \quad \rho_h = 995.12\ \text{kg/cm}^3$$

yielding τ = 22.8 seconds. The density values are taken from Weast (1986). The initial value for h_1 is 12.04 cm in the cold room, since the tank is filled to 1 cm above the top of the doorway. Thus, $H(0) \equiv H_0$ is 1.09. Eq. (5) is integrated analytically and H is written as an implicit function of t*.

$$t^* = \ln\left([1 + \sqrt{3/H_0}\,]\,[1 - \sqrt{3/H}\,] \,/\, [(1 - \sqrt{3/H_0}) \cdot (1 + \sqrt{3/H})]\right)^{\sqrt{3}} \qquad (7)$$

Equation (7) was solved for the time history of H in the cold room and the results are tabulated in the Table I.

Time, t (s.)	H
0	1.090
5	0.944
10	0.799
15	0.657
20	0.521
25	0.395
30	0.282
35	0.184
40	0.104
45	0.046
50	0.010
55.1	0.000

Table I. The time history of H from Eq. (7) for the conditions in the experiment.

From these results, we note that H does not reach zero asymptotically, but at a definite time which for this case is $t^*(H=0) = \ln(4.035)^{\sqrt{3}} = 2.42$ as determined from Eq. (7). In this regard it is much like the emptying of a tank through an orifice; a situation that also results in a finite emptying time. The time required for the thermocline to move from an initial position H(0) to the doorway midheight is an equilibration time which from Eq. (7) is

$$t^*(H=0) = \ln\left([\sqrt{3/H_0} + 1] \,/\, [\sqrt{3/H_0} - 1]\right)^{\sqrt{3}} \qquad (8)$$

Equation (8) is plotted in Figure 5. While this is strictly valid for $H_0 < 3$, the maximum value of H_0 for which Eq. (8) applies will be smaller than this because of entrainment above the doorway top and below its lower sill.

DISCUSSION OF RESULTS

The most striking feature of the data presented in Figures 2 and 3 is the presence of internal waves which are excited by the sudden onset of flow through the doorway. Their frequency is close to the buoyancy frequency. They are not quickly damped, but survive for about 10 cycles. To render these waves visible, multicolor dyes were introduced just prior to opening the door. The dyes were poured, drop by drop, from a

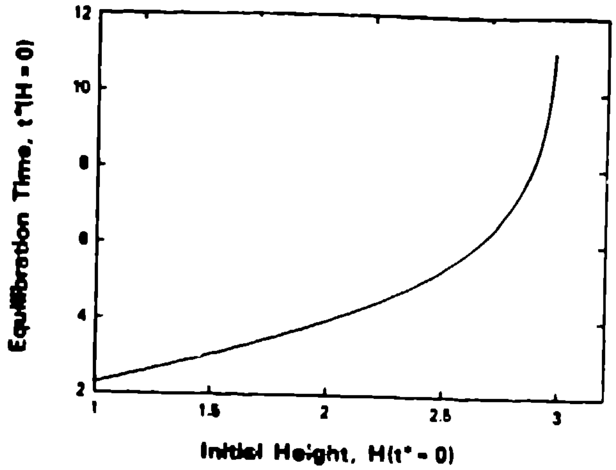

Fig. 5 Equilibration time, t*(H=0), as a function of the dimensionless initial height of the thermocline, H(0).

height of 5 cm above the water surface. Each drop produced a shower of descending whisp-like plumes much like an aerial fireworks display extending about 25 cm below the surface. The individual plumes retained their separate identity for up to 10 minutes except in regions of turbulence or high entrainment. The three colors gave some depth discrimination. No photographs were taken, but the observations can be summarized as follows. After opening the door, the flow was established within a couple of seconds, and the visible action was most intense in the upper region of the cold room and the lower region of the hot room. It appeared much like waves breaking on a beach (of course, we are speaking of internal waves - there was no observed surface wave action). This intense wave breaking phase (which some might characterize as being turbulent) subsides in about 15 seconds to a more-laminar flow where undulations of the dye streaks show the occurrence of internal waves at frequencies consistent with the temperature data of Figure 2. The entrainment of the cold fluid by the incoming hot flow (in the cold room) is clearly evident as much of the blue dye (which was centrally located in the cold room) was swept up with the hot flow. Similarly, the hot fluid is entrained by the cold flow in the hot room. The flows are three dimensional and complex, and much could be learned by a proper photographic analysis.

Such waves have not normally been observed in laboratory experiments [none were seen in Yewell et al. (1982), Hamblin and Ivey (1983), or Ivey (1984)], but they seem ever present in the computational experiments (Gallagher et al. 1978; Patterson and Imberger, 1980; Lee and Korpela, 1983; Han, 1984; Hyun, 1985). Ivey (1984) raises the question as to whether the waves are only a result of numerical instabilities, since he and others looked for them in vain under conditions that Patterson and Imberger (1980) had indicated that they should be found. Hyun (1985) presents evidence that his waves did not result from numerical experiments. But it seems possible that the natural convection boundary layer is sometimes too gentle a disturbance to excite these waves. That was the position of Sakurai and Matsuda (1972) and of Jischke and Doty (1975) in their analytical treatments. Their position is simply based upon the idea that the startup time for a boundary layer is always longer than the period of the Brunt-Vaisala oscillation (easily demonstrated by scale analysis).

So even if the wall temperatures can be changed instantaneously, the boundary layer will still develop its motion over a time longer than the internal wave period. Furthermore, if the core of the enclosure is initially of uniform temperature (as is the case in most of the works cited above), there is no potential for the existence of waves in the core. It takes time to develop the stratification temperature distribution in the core. In the references cited above, the flows were all driven by natural convection boundary layers in undivided enclosures, a rather gentle disturbance. The situation is quite different in our experiment where large quantities of fluid are exchanged rapidly between the two rooms, and so it is not surprising that waves prove to be a significant feature of the flow.

We had expected less entrainment by the counter-flowing streams, and a sharper thermocline. The simple model presented above reflects that thinking. But substantial flow entrainment is evident from visual observation of the dye plumes, and by the behavior of the temperature profiles in Figure 3. If there had been no mixing, then the process would result in the entire upper half of the enclosure being hot, and the lower half to be cold (in both rooms). So, what basis can there be for a comparison of the simple model with the experiment?

First, one can state that the tabulated distributions for H, given above, show a time dependence that is fairly close to what is observed. More specifically, one can compare the total time duration of 55.1 seconds for the theory with the experimental crossover points at 72 and 69 seconds for the central thermocouple pairs (3 and 13, and 4 and 14) shown in Figure 3 as mentioned above. Also, the initial velocity of the thermocline (i.e., dh_1/dt) can be computed from the model to be 0.32 cm/s; the measured values were about 0.4 cm/s as determined from Figure 2 by observing the initial response of thermocouples 5, 6, 11, and 12. So then it appears that a simple model that ignores internal wave phenomena and entrainment does fairly well in predicting the equilibration time for the process.

CONCLUSIONS

We have performed laboratory experiments and numerical calculations to investigate the development of flow and thermal stratification in a partially divided enclosure. The most striking feature of the data is the presence of internal waves which are excited by the sudden onset of flow through a small opening in the partition.

The internal waves are characterized by two distinct phases: 1) a period of intense internal-wave breaking lasting about 15 seconds into the experiment, and 2) a period of less-intense laminar-like internal wave motion having a frequency ranging from 0.5 to 0.10 hz and lasting for about 10 cycles. A highly damped, low-frequency "sloshing" mode with a period of over 100 seconds also persists during establishment of the flow and stratification. Internal waves have not normally been observed in laboratory experiments where flows are driven by natural convection boundary layers. This is quite different from our experiments where large quantities of fluid are exchanged between the partially divided zones.

Temperature histories show that the time to establish equilibrium conditions is in general agreement with that predicted by a formula from a simple orifice model. The model assumes that interzonal flow is driven by only hydrostatic pressure differences between the zones and ignores internal wave formation and entrainment.

We are currently modifying an existing simplified model for interzonal heat and mass transport through a doorway (Jones et al. 1985a) to include entrainment but still ignoring the internal wave phenomena. The principal elements in it are the core models which are connected to each other through the simple doorway model described above. The cores entrain all flow through the doorways in addition to fluid flows originating possibly from boundary layers and thermal plumes at core boundaries of different temperatures. The model has undergone preliminary validation (Jones and Balcomb, 1985b). Although there are no noteworthy results to report yet from this new phase, preliminary indications are that such simple models are quite capable of accurately predicting transient and quasi-steady aperture flows and stratification temperature gradients in the cores.

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REFERENCES

Anderson, R., Fisher, E. M., and Bohn, M., 1985, "Natural Convection in a Closed Cavity with Variable Heating of the Floor and One Vertical Wall," Submitted to Int. J. Heat Mass Transfer.

Balcomb, J. D. and Yamaguchi, K., 1983, "Heat Distribution by Natural Convection," Proceedings of the 8th National Passive Solar Conference, Santa Fe, NM.

Balcomb, J. D., Jones, G. F., and Yamaguchi, K., 1984, "Natural Convection Airflow Measurement and Theory," Proceedings of the 9th National Passive Solar Conference, Columbus, Ohio.

Balcomb, J. D. and Jones, G. F., 1985, "Natural Air Motion in Passive Solar Buildings," Los Alamos National Laboratory report LA-UR-85-1045, Los Alamos National Laboratory, Los Alamos, NM.

Bauman, F., Gadgil, A., Kammerud, R., and Greif, R., 1980, "Buoyancy-Driven Convection in Enclosures: Experimental Results and Numerical Calculations," ASME Paper 80-HT-66, American Society of Mechanical Engineers, New York.

Brown, W. G. and Solvason, K. R., 1962, "Natural Convection Through Rectangular Openings in Partitions, Part 1: Vertical Partitions," Int. J. Heat and Mass Transfer, Vol. 5, pp. 859-868.

Gadgil, A., Bauman, F., Altmayer, E., and Kammerud, R. C., 1984, "Verification of a Numerical Simulation Technique for Natural Convection," J. Heat Transfer, Vol. 106, pp. 366-369.

Gallagher R. H., Liggett, J. A., and Young, D. L., 1978, Finite Elements in Fluids, Vol. 3, Chapt. 13, ed. R.H. Gallagher, John Wiley, New York.

Hamblin, P. F. and Ivey, G. N., 1983, "Convection Near the Temperature of Maximum Density Due to Horizontal Temperature Differences," Submitted to J. Fluid Mech.

Han, S. M., 1984, "A Transient Numerical Analysis of High Rayleigh Number Convection in a Differentially Heated Square Cavity," ASME Paper 84-HT-57, American Society of Mechanical Engineers, New York.

Hill, D. A., Kirkpatrick, A., and Burns, P., 1985, "Interzonal Natural Convection Heat Transfer in a Passive Solar Building," Presented at the 23rd AIChE/ASME National Heat Transfer Conference, Denver, Colorado.

Hyun, J. M., 1985, "Transient Buoyant Convection of a Contained Fluid Driven by the Changes in the Boundary Temperatures," J. Appl. Mech., Vol. 52, pp. 193-198.

Ivey, G. N., 1984, "Experiments on Transient Natural Convection in a Cavity," J. Fluid Mech., Vol. 144, pp. 389-401.

Jischke, M. C. and Doty, R. T., 1975, "Linearized Buoyant Motion in a Closed Container," J. Fluid Mech., Vol. 71, pp. 729-754.

Jones, G. F., Balcomb, J. D., and Otis, D. R., 1985a, "A Model for Thermally Driven Heat and Air Transport in Passive Solar Buildings," ASME Paper 85-WA/HT-69, American Society of Mechanical Engineers, New York.

Jones, G. F. and Balcomb, J. D., 1985b, "Validation of a Simplified Model for Thermally Driven Heat and Air Transport in Passive Solar Buildings," Proceedings of the 10th National Passive Solar Conference, Raleigh, North Carolina, Vol. 10, pp. 75-81.

Kahwaji, G., Burns, P., and Winn, C. B., 1985, "Convection Studies in The Sunspace of the REPEAT Facility," ASME Paper 85-WA/SOL-12, American Society of Mechanical Engineers, New York.

Kirkpatrick, A. and Bohn, M., 1983, "High-Rayleigh-Number Natural Convection in an Enclosure Heated from Below and from the Sides," Presented at the 21st ASME/AIChE National Heat Transfer Conference, Seattle, Washington.

Kirkpatrick, A. and Bohn, M., 1985, "Flow Visualization and Stratification in High Rayleigh Number Mixed Cavity Natural Convection," ASME Paper 85-HT-38, American Society of Mechanical Engineers, New York.

Lee, Y. and Korpela, S. A., 1983, "Multicellular Natural Convection in a Vertical Slot," J. Fluid Mech., Vol. 126, pp. 91-121.

Nansteel, M. W. and Greif, R., 1981, "Natural Convection Undivided and Partially Divided Enclosures," J. Heat Transfer, Vol. 103, pp. 623-629.

Nansteel, M. W. and Greif, R., 1984, "An Investigation of Natural Convection in Enclosures with Two- and Three-dimensional Partitions," Int. J. Heat Mass Transfer, Vol. 27, pp. 561-571.

Patterson, J. and Imberger, J., 1980, "Unsteady Natural Convection in a Rectangular Cavity," J. Fluid Mech., Vol. 100, pp. 65-86.

Saskurai, T. and Matsuda, T., 1972, "A Temperature Adjustment Process in a Boussinesq Fluid via a Buoyancy-Induced Meridonal Circulation," J. Fluid Mech., Vol. 54, pp. 417-421.

Weast, R. C., Ed., 1986, CRC Handbook of Chemistry and Physics, 67th edition, CRC Press, Cleveland, Ohio.

Yamaguchi, K., 1984, "Experimental Study of Natural Convection Heat Transfer Through an Aperture in Passive Solar Buildings," Proceedings of the 9th National Passive Solar Conference, Columbus, Ohio.

Yewell, R., Poulikakos, D., and Bejan, A., 1982, "Transient Natural Convection Experiments in Shallow Enclosures," J. Heat Transfer, Vol. 104, pp. 533-538.